High spin negative parity states in ^{35}Cl (populated in ^{32}S(α,pγ)^{35}Cl)

1974 J. Phys. A: Math. Nucl. Gen. 7 1977

(http://iopscience.iop.org/0301-0015/7/16/002)

J. Phys. A: Math., Nucl. Gen., Vol. 7, No. 16, 1974. Printed in Great Britain. © 1974

High spin negative parity states in ^{35}Cl

P R G Lornie, E M Jayasinghe†, G D Jones, H G Price, M F Thomas, P J Twin and P J Nolan

Oliver Lodge Laboratory, University of Liverpool, PO Box 147, Liverpool L69 3BX, UK

Received 28 May 1974

Abstract. The nucleus ^{35}Cl has been studied using the reaction ^{32}S $(\alpha, p\gamma)^{35}$Cl. Proton–gamma ray angular correlations have been measured using an E/DE telescope to detect the protons. Gamma ray linear polarizations have been measured with a three Ge(Li) Compton polarimeter. The levels at 4348 keV, 5408 keV and 6088 keV have been shown to have spins and parities of $\frac{9}{2}^-$, $\frac{11}{2}^-$ and $\frac{13}{2}^-$ respectively. Branching ratios and electromagnetic multipole mixing ratios were also determined The lifetime of the 5408 keV level was measured to be 400 ± 100 fs by the Doppler shift attenuation method, and a lifetime of $9{\cdot}3 \pm 0{\cdot}8$ ps was obtained by the recoil distance method for the 6088 keV level. Electromagnetic transition strengths were deduced for the decays of these levels and were found to be inconsistent with the levels being interpreted as members of a rotational band based on the $\frac{7}{2}^-$ level at 3163 keV.

1. Introduction

The nucleus ^{35}Cl has received considerable experimental attention in recent years. A summary of present knowledge of this nucleus is given by Endt and van der Leun (1973). Proton–gamma ray angular correlations have been measured by Hooton *et al* (1970) using the reaction ^{32}S$(\alpha, p\gamma)^{35}$Cl, and the same reaction has been used by Ingebretsen *et al* (1969) and Broude *et al* (1972) to measure lifetimes of excited states in this nucleus. On the basis of the available experimental data, Ingebretsen *et al* (1970) have proposed a ground state $K = \frac{3}{2}^+$ rotational band. Rotational structure has also been observed in this region of the s–d shell in negative parity states of ^{29}Si (Viggars *et al* 1973) in which there is a rotational band based on the low lying $\frac{7}{2}^-$ level. In ^{35}Cl the $\frac{7}{2}^-$ level is at 3163 keV and a candidate for the $\frac{9}{2}^-$ was identified by Hooton *et al* (1970) at 4348 keV $(\frac{5}{2}, \frac{9}{2})^-$. Alenius and Wallander (1973) have reported levels at 5407 keV and 6086 keV which decayed through the $\frac{7}{2}^-$ level at 3163 keV. From the yield of the associated γ rays as a function of beam energy they suggest that the levels may have spins of $\frac{11}{2}^-$ (5407 keV) and $\frac{13}{2}$ (6086 keV).

The present work was performed to definitely establish the spins and parities of these states, and to determine their electromagnetic decay properties so that the suggestion of Alenius and Wallander that these states form a rotational band could be tested.

2. Experimental method and data analysis

The states in ^{35}Cl were populated by the reaction ^{32}S$(\alpha, p\gamma)^{35}$Cl, $Q = -1{\cdot}863$ MeV. Proton–gamma ray angular correlations were measured at an incident α particle energy

† Now at University of Colombo, Colombo, Sri Lanka.

of 14·7 MeV, and lifetimes and γ ray linear polarization measurements were performed at α particle energies of 11·0 MeV and 12·0 MeV. In all the experiments natural sulphur in the form of cadmium sulphide was used as the target material. The targets for the p–γ experiment were self-supporting and had a thickness of about 100 $\mu g\,cm^{-2}$, whilst the target for the polarization and lifetime experiment was 1 $mg\,cm^{-2}$ thick and was supported on a thick gold backing.

In the correlation experiment particles were detected using an annular E/DE telescope accepting particles emitted close to 180° with respect to the beam direction. The use of an E/DE counter enabled protons from the $^{32}S(\alpha, p\gamma)^{35}Cl$ reaction to be distinguished from α particles from the competing $^{32}S(\alpha, \alpha'\gamma)^{32}S$ inelastic scattering. The resolution of the counter system for protons in the experiment was about 80 keV (FWHM). Gamma rays were detected in five 5 in × 6 in NaI(Tl) detectors mounted in a horizontal plane around the target chamber at angles of 8°, 30°, 45°, 90° and 120° (60°) with respect to the beam direction. In addition a Ge(Li) detector was mounted vertically above the target chamber, to assist in the determination of the decay scheme and to yield accurate γ ray energies. Coincidences were recorded between these six γ ray detectors and the particle detector, and written event by event onto magnetic tape for subsequent analysis. A portion of the data was analysed on-line to allow the progress of the experiment to be monitored.

Gamma ray linear polarizations were measured at 90° to the beam direction using a three Ge(Li) Compton polarimeter. This apparatus and its calibration have been described in detail by Butler *et al* (1973). Simultaneously with the polarization measurement an escape-suppressed spectrometer (Sharpey-Schafer *et al* 1971) was used to measure the angular distribution of the γ rays. The peak counts at each angle were normalized using the isotropic 1220 keV γ ray from the $\frac{1}{2}^+$ first excited state of ^{35}Cl. These angular distributions arise from the decay of states with the same alignment parameters as the polarization results and are important for the analysis of those data. Also γ ray centroid shifts were extracted from these angular distribution data and used to determine the lifetimes of the levels by the Doppler shift attenuation method. In the case of the 6088 keV level, no Doppler shift was observable, and a further experiment was performed to measure the lifetime of this level by the recoil distance (plunger) method. The basis of this technique is that the target is supported on the back of a thin gold foil such that the residual nucleus recoils into vacuum and is then brought to rest in a stopper foil positioned a few micrometres way. The apparatus and analysis technique have been described by Nolan *et al* (1973) and the distance scale was established in the present experiment by the capacitance measurement technique.

The phase convention of Rose and Brink (1967) was used throughout the data analysis. The measured γ ray angular distributions were tested against the predicted distributions for various spin hypotheses and the electromagnetic multipole mixing ratio δ varied to minimize R, the sum of squares of residuals. R_{min} was assumed to be drawn from a χ^2 distribution with the appropriate number of degrees of freedom and a spin hypothesis was rejected if no value of δ gave a value of R below the 0·1 % confidence limit. In making the theoretical prediction of the distribution it is necessary to include an estimate of the alignment of the state. Detection of the outgoing proton close to 180° in the p–γ correlation experiment means that the population of magnetic substates other than those with $m = \pm\frac{1}{2}$ is expected to be negligible (Litherland and Ferguson 1961). The data from the polarization experiment were treated similarly, but the absence of a geometrical constraint meant that an alternative means of determining the alignment of the initial state had to be used. The compound nucleus statistical model was used to describe the reaction and the computer program MANDY of Sheldon and van Patter (1966) was used to predict the substate populations. It was found that the transmission coefficients for the outgoing proton allowed the population of all substates with $m \geqslant \frac{5}{2}$ to be fixed at zero, the first and second substates were allowed to vary freely. In practice for high spin states the alignment parameter is insensitive to the distribution of the population among the substates of low magnetic quantum number. The value of the polarization, and the values of δ for various spin hypotheses determined from the coincidence experiments were included as extra data points at this stage, and their residuals included in R, as described by James *et al* (1974), whose procedure for determining errors on δ was also adopted.

In the analysis of the lifetime data a straight line was fitted to centroid shift against $\cos\theta$, where θ is the angle of detection of the γ ray. The ratio of the slope of this line to the slope produced by an unattenuated Doppler shift calculated from the kinematics is the attenuation factor F. The relationship between F and the mean lifetime τ_m depends upon the slowing down of the recoiling ion in the target and backing, and was calculated using the method of Blaugrund (1966).

3. Results

The Legendre coefficients, corrected for solid angle effects, measured linear polarizations and branching ratios, and the mixing ratios, spins and parities and transition strengths deduced from these are presented in table 1.

3.1. The 4348 keV level

The branching ratio observed for this level in the present experiment was $64 \pm 2\%$ to the 3163 keV level and $36 \pm 2\%$ to the 2646 keV level agreeing better with that of Hooton *et al* (1970) than that of Broude *et al* (1972). Hooton *et al* restricted the spin of the level to $\frac{5}{2}$ or $\frac{9}{2}$. The lifetime measurement of Broude *et al* (1972), $2{\cdot}9^{+1{\cdot}4}_{-0{\cdot}7}$ ps showed that the level has negative parity from transition strength arguments, but the spin ambiguity remained unresolved. Our angular distribution measurements on the cascade through the 3163 keV level yield results in agreement with Hooton *et al* (1970) and Alenius and Wallander (1973), $\delta = 0{\cdot}36 \pm 0{\cdot}03$ for spin $\frac{9}{2}$ and $-0{\cdot}85 \pm 0{\cdot}02$ for spin $\frac{5}{2}$. The angular distribution of the decay to the 2646 keV level was also measured and yielded possible mixing ratios of $0{\cdot}0 \pm 0{\cdot}03$ for spin $\frac{9}{2}$ and $-0{\cdot}12 \pm 0{\cdot}04$ or greater than 7 for spin $\frac{5}{2}$. The larger value of δ for spin $\frac{5}{2}$ may be rejected since it requires an M2 strength 32^{+16}_{-8} Wu. The polarization of the major decay branch does not distinguish between the two spin hypotheses, however the polarization of the 1702 keV γ ray was measured to be $0{\cdot}36 \pm 0{\cdot}07$ which when fitted together with the previous measurement of δ and the simultaneous angular distribution of the 1702 keV level allowed rejection of the $\frac{5}{2}^-$ hypothesis at the $0{\cdot}1\%$ confidence level, as shown in figure 1. The level is therefore concluded to have spin and parity $\frac{9}{2}^-$.

3.2. The 5408 keV level

This level decays $91 \pm 2\%$ to the 3163 keV level and $9 \pm 2\%$ to the 4348 keV level. This is a smaller branch to the 4348 keV level than that of 26% reported by Alenius and Wallander (1973). The angular distribution of the 2245 keV γ ray from the coincidence

Table 1.

E_{level} (keV)	E_γ (keV)	J^π	J_f^π	Branch (%)	Solid angle corrected Legendre coefficients a_2	a_4	Polarization $P(90°)$	Mixing ratio δ	F factor	$\tau_m \pm 25\%$†	$M(E2)^2$ (Wu)	$M(M1)^2$ (mWu)
4348	1185	$\frac{9}{2}^-$	$\frac{7}{2}^-$	64 ± 2	-0.95 ± 0.03	0.08 ± 0.03	-0.005 ± 0.040	0.36 ± 0.03			1.3 ± 0.5‡	4.0 ± 1.5‡
	1702	$\frac{9}{2}^-$	$\frac{7}{2}^+$	36 ± 2	-0.34 ± 0.05	0.04 ± 0.05	0.36 ± 0.07	0.0 ± 0.03				
5408	1060	$\frac{11}{2}^-$	$\frac{9}{2}^-$	9 ± 2	0.19 ± 0.11	-0.01 ± 0.13	-0.40 ± 0.14	-0.25 ± 0.08	0.50 ± 0.05§	400 ± 100 fs	1.1 ± 0.3	5 ± 1.3
	2245	$\frac{11}{2}^-$	$\frac{7}{2}^-$	91 ± 2	0.44 ± 0.03	-0.19 ± 0.03		0.0 ± 0.03			4.5 ± 1.1	
6088	680	$\frac{13}{2}^-$	$\frac{11}{2}^-$	85 ± 5	-0.22 ± 0.01	0.005 ± 0.015	-0.45 ± 0.05	-0.02 ± 0.01		9.3 ± 0.8 ps	0.05 ± 0.05	8.5 ± 1
	1740	$\frac{13}{2}^-$	$\frac{9}{2}^-$	15 ± 5								

† An error of $\pm 25\%$ is included in the time scale to allow for systematic errors in the stopping theory.
‡ These values are calculated from the lifetime measurement of Broude *et al* (1972).
§ Corrected for feeding by the 6088 keV level.

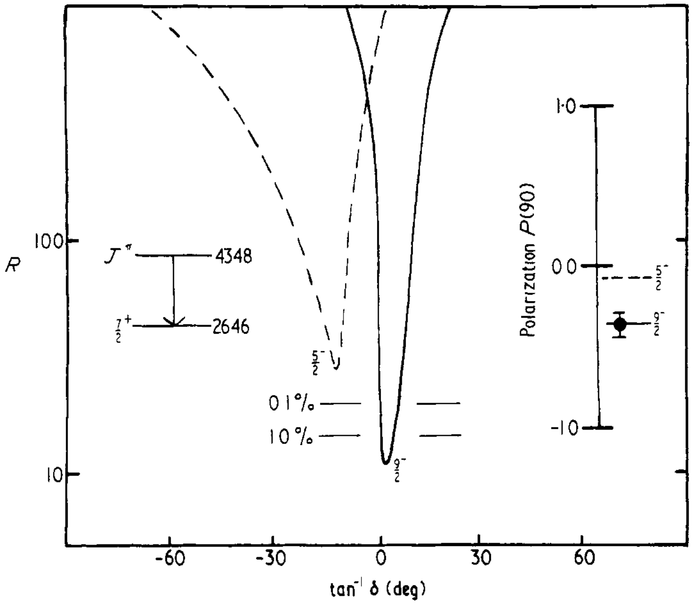

Figure 1. The 4348 keV level: a plot of R against $\tan^{-1}\delta$ for the two possible spin hypotheses $J = \frac{5}{2}^-$ and $\frac{9}{2}^-$. The data included in R are the singles angular distribution of the 1702 keV γ ray, the linear polarization of this γ ray, and the measurement of δ from the coincidence experiment (0·0 ± 0·03). $J = \frac{5}{2}^-$ is rejected at the 0·1 % confidence level.

experiment rejects all spin hypotheses except $J = \frac{7}{2}$ or $\frac{11}{2}$. Including the subsequent 3163 keV γ ray in the fit rejects the $\frac{7}{2}$ hypothesis at the 0·1 % confidence level yielding $J = \frac{11}{2}$ with $\delta = 0{\cdot}0 \pm 0{\cdot}03$ (as shown in figure 2). The mixing ratio of the weak 1060 keV branch was measured to be $-0{\cdot}25 \pm 0{\cdot}08$. The polarization of the 2245 keV γ ray could not be measured since in the polarimeter it was not resolved from the strong 2230 keV γ ray from the first excited state of ^{32}S. However the polarization of the weaker 1060 keV γ ray was measured to be $-0{\cdot}42 \pm 0{\cdot}14$ which when fitted with the associated angular distribution and the mixing ratio measured in the coincidence experiment showed the level to have negative parity (as shown in figure 2). The attenuation factor for the Doppler shift of the 1060 keV γ ray was, after correction for feeding by the 6088 keV level, $0{\cdot}50 \pm 0{\cdot}06$ which yields a lifetime of 400 ± 100 fs for this level.

3.3. The 6088 keV level

The decay modes of the 6088 keV and 6140 keV levels were established by setting windows on the lower and upper sides of the particle peak. The 6140 keV level was weakly excited and decays mainly to ground, whilst the strongly excited 6088 keV level decays 85 ± 5 % to the 5408 keV level and 15 ± 5 % to the 4348 keV level. This latter branch is established by the presence of a 1740 keV γ ray in the coincidence Ge(Li) spectrum, and the size determined by the intensity of the 1185 and 1060 keV γ rays in coincidence with the outgoing protons from this level, as the 1740 keV γ ray was not resolved in the NaI(Tl) spectra. The angular distribution of the 680 keV γ ray and the subsequent 2245 keV γ ray from the coincidence experiment restrict the spin of the 6088 keV level to either $J = \frac{9}{2}$ with $\delta = -0{\cdot}045 \pm 0{\cdot}014$ or $J = \frac{13}{2}$ with $\delta = -0{\cdot}020 \pm 0{\cdot}015$. The linear

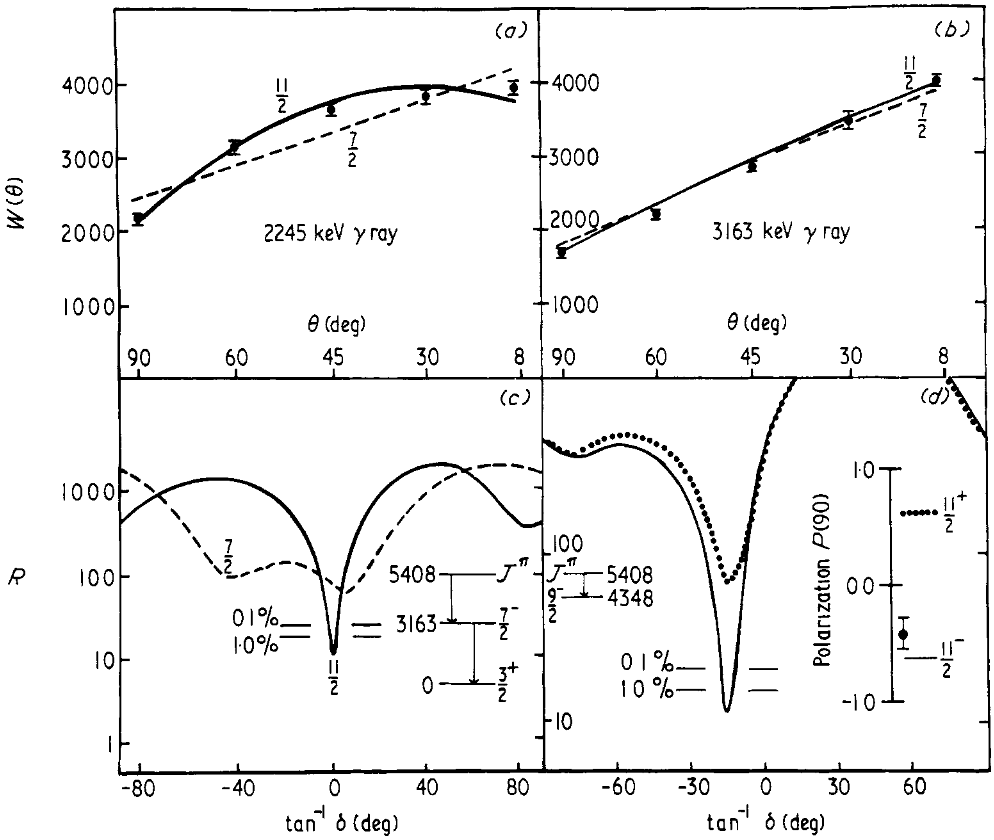

Figure 2. The 5408 keV level: the angular distributions of (*a*) the 2245 keV γ ray and (*b*) the subsequent 3163 keV γ ray obtained in the proton–γ ray coincidence experiment. Fits to the data are shown for the spin hypotheses $J = \frac{7}{2}$ and $J = \frac{11}{2}$. (*c*) R plotted against $\tan^{-1}\delta$ for the fit to these data is shown and rejects the $J = \frac{7}{2}$ hypothesis at the 0·1% confidence level. (*d*) R plotted against $\tan^{-1}\delta$ for the data on the 1060 keV γ ray. The sum of squares of residuals R includes the singles angular distribution, the polarization and the previously measured value of δ of $-0{\cdot}25 \pm 0{\cdot}08$. This plot establishes negative parity for the level.

polarization of the 680 keV γ ray was measured to be $-0{\cdot}45 \pm 0{\cdot}05$. This was fitted together with the values of δ from the coincidence experiment and the angular distribution, and figure 3 shows that a value of R_{min} below the 0·1 % confidence level was obtained only for the hypothesis $J = \frac{13}{2}^-$. The Doppler shift attenuation factor for this γ ray was $-0{\cdot}09 \pm 0{\cdot}09$ which gives a lower limit of 3·5 ps for the lifetime of this level, and a subsequent experiment was performed to measure the lifetime by the recoil distance technique. The fit to the plunger data, which is shown in figure 4, fixes the lifetime as $9{\cdot}3 \pm 0{\cdot}8$ ps.

4. Discussion

The 4348, 5408 and 6088 keV levels in ^{35}Cl have been definitely shown to have spins and parities of $\frac{9}{2}^-$, $\frac{11}{2}^-$ and $\frac{13}{2}^-$ respectively, confirming previous suggestions of Hooton

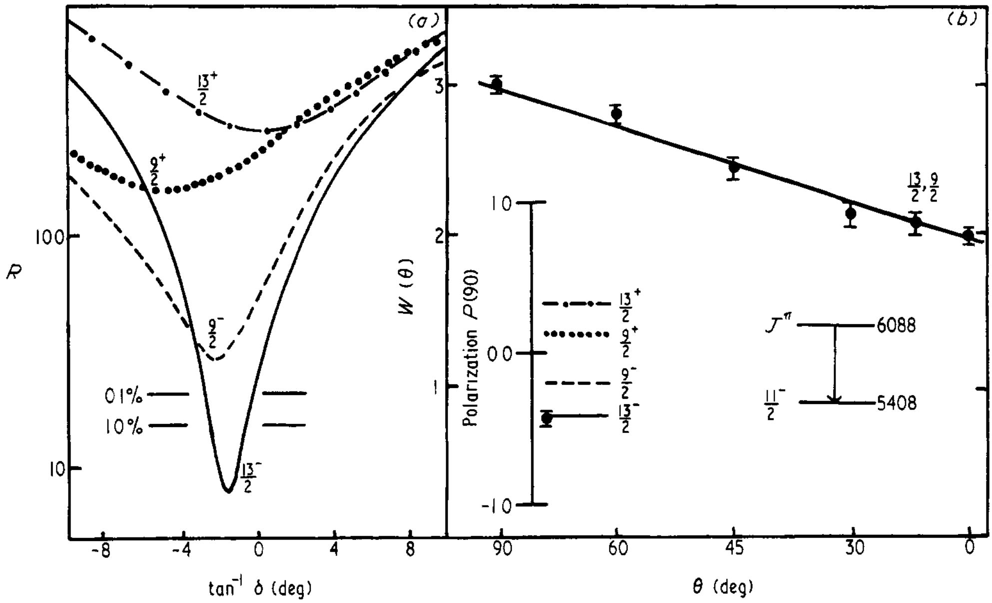

Figure 3. The 6088 keV level: (*a*) R plotted against $\tan^{-1}\delta$ for the data on this level. R includes the singles angular distribution, the linear polarization and the previously measured δ values for the spin hypotheses $J = \frac{9}{2}$ and $J = \frac{13}{2}$. Only the hypothesis $J = \frac{13}{2}^-$ gives a value of R_{min} lying below the 0·1 % confidence level. (*b*) the singles angular distribution, and the linear polarization of the 680 keV γ ray, together with the best fits for $J = \frac{9}{2}$ and $J = \frac{13}{2}$.

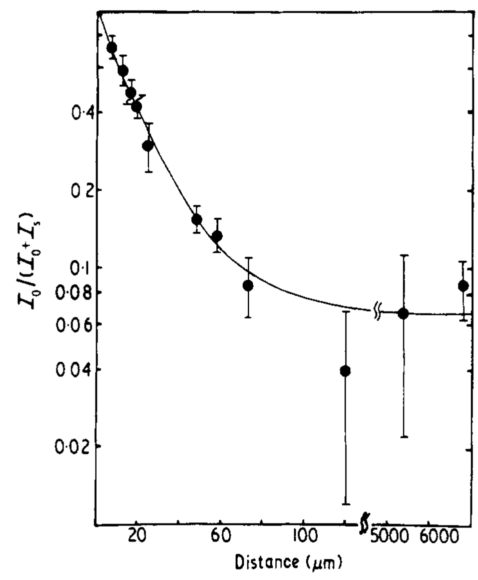

Figure 4. The recoil distance method measurement of the lifetime of the 6088 keV level in ^{35}Cl. The data were obtained from the 680 keV γ ray, and are plotted as the ratio of the intensity of the stopped peak to the total intensity $I_0/(I_0 + I_s)$ against the distance between the target and the stopper. The full curve is the best fit to the data, and is constrained to pass through the point (0·0, 1·0). The fit corresponds to a lifetime of $9{\cdot}3 \pm 0{\cdot}8$ ps.

et al (1970) and Alenius and Wallander (1973). These latter authors further proposed that the levels might be members of a rotational band based on the $\frac{7}{2}^-$ 3163 keV level even though the excitation energies of the states do not follow a simple $J(J+1)$ relationship characteristic of rotational structure. The present results have enabled E2 transition strengths to be determined for decays between these levels and the values of $1{\cdot}3 \pm 0{\cdot}5$, $1{\cdot}1 \pm 0{\cdot}3$, $4{\cdot}5 \pm 1{\cdot}1$ and $0{\cdot}05 \pm 0{\cdot}05$ Wu indicate that in only one transition is there any enhancement over the single-particle estimates. We, therefore, conclude from this absence of large E2 strengths that the levels are not members of a rotational band. We note that a further feature of the decays between these levels is that the three M1 strengths are small with values approximately 5 mWu.

Shell-model calculations for mass 35 by Erné (1966) and Maripuu and Hokken (1970) predicted low lying negative parity states of high spin, but because of the extremely restricted configuration space employed the agreement with the experimental energy spectrum is only qualitative. We are, at present, extending these calculations to include transition strengths as well as excitation energies and also using a larger configuration space.

Acknowledgments

This work was supported by the Science Research Council, and one of us PRGL acknowledges the support of an SRC research studentship during the period of the work. The assistance of P A Butler with the setting up and calibration of the polarimeter is also gratefully acknowledged. We also wish to thank Mr J Reynolds for making the various targets and Mr M Patterson for manufacturing the surface barrier detectors.

References

Alenius N and Wallander E 1973 *Phys. Scripta* **8** 119–34
Blaugrund A E 1966 *Nucl. Phys.* **88** 501–12
Broude C, Forster J and Ingebretsen F 1972 *Nucl. Phys.* A **192** 291–304
Butler P A *et al* 1973 *Nucl. Instrum. Meth.* **108** 497–502
Endt P M and van der Leun C 1973 *Nucl. Phys.* A 214
Erné F C 1966 *Nucl. Phys.* **84** 91–105
Hooton B W, Häusser O, Ingebretsen F and Alexander T K 1970 *Can. J. Phys.* **48** 1259–69
Ingebretsen F, Alexander T K, Häusser O and Pelte D 1969 *Can. J. Phys.* **47** 1295–306
Ingebretsen F, Broude C, Forster J S 1970 *Phys. Lett.* **31B** 297–9
James A N, Twin P J and Butler P A 1974 *Nucl. Instrum. Meth.* **115** 105–13
Litherland E and Ferguson A J 1961 *Can. J. Phys.* **39** 788
Maripuu S and Hokken G A 1970 *Nucl. Phys.* A **141** 481–96
Nolan P J *et al* 1973 *J. Phys.* A: *Math., Nucl. Gen.* **6** L37–40
Rose H J and Brink D M 1967 *Rev. Mod. Phys.* **39** 306–47
Sharpey-Schafer J F *et al* 1971 *Nucl. Phys.* A **167** 602–4
Sheldon E and van Patter D 1966 *Rev. Mod. Phys.* **38** 143–86
Viggars D A *et al* 1973 *J. Phys.* A: *Math., Nucl. Gen.* **6** L67–72